AIR FORCE RESEARCH LABORATORY SPACECRAFT CRYOCOOLER ENDUANRANCE EVALUATION UPDATE: FY98-99

B. J. Tomlinson[1], 2nd Lt C. Yoneshige[2], N. Abhyankar[3]

[1,2]Air Force Research Laboratory
Kirtland AFB, NM USA 87117

[3]Dynacs Engineering Co. Inc.
Albuquerque, NM, 87123

ABSTRACT

The need for long term endurance evaluation data on space cryocoolers has long been an issue due to the 10-year plus design life of this technology and the absence of any accepted accelerated testing methodology. The Air Force Research Laboratory (AFRL), under sponsorship from the Ballistic Missile Defense Organization (BMDO), has been evaluating the long term performance of space cryocooler technology for the past five years to provide feedback to system designers and cryocooler developers to help mitigate or correct identified deficiencies. Cryocooler technology under evaluation at AFRL includes units from TRW, Creare, and Raytheon utilizing a variety of refrigeration cycles including Stirling, Pulse Tube (Stirling variant), Reverse Brayton cycles, and technological maturity. Cryocoolers are instrumented in state-of-the-art experiment stands utilizing software driven data acquisition systems that collect temperature, power, current, and voltage measurements. This allows critical cryocooler operating parameters to be closely tracked in order to quantify the technology's ability to meet the 5 to 10 year lifetime. It also allows AFRL to observe and document any long-term changes in cryocooler performance. Endurance data has been collected on 10 cryocoolers, some of which have been in operation for nearly 5 years. This paper includes experiment philosophy, lessons learned, and conclusions from the endurance evaluation program at AFRL for FY 98-99.

INTRODUCTION

Air Force, BMDO, and Department of Defense (DoD) investment in the development of space cryogenic coolers rests primarily on the critical characteristics of *lifetime and reliability.* This distinguishes the capabilities of long-life space cryocoolers from short-

lived tactical units. Assessing cryocooler lifetime, reliability, and thermodynamic performance is the primary focus of AFRL's cryocooler characterization and endurance evaluation activities.

The primary focus of the current BMDO funded and AF cryocooler development efforts is to support the Engineering Manufacturing Development (EMD) requirements for the SBIRS Low satellite program. The SBIRS Low system is an integral part of the space based infrared architecture and provides the warfighter with essential over the horizon mid-course tracking to enable Ballistic Missile Defense (BMD) of the CONUS and theater, missile warning, technical intelligence, and battle space characterization (including space surveillance), and SBIRS Low is the only program currently in development to provide mid-course tracking.

SBIRS Low has utilized and baselined several AFRL developed cryocooler technologies for the TRW / Raytheon Flight Demonstration System (FDS). Although now cancelled, the experiment was to include two TRW 150K mini-pulse tubes and the Raytheon Improved Standard Spacecraft Cryocooler (ISSC). The ISSC itself had leveraged off of the designs for the Raytheon Standard Spacecraft Cryocooler (SSC) and Raytheon Prototype Spacecraft Cryocooler (PSC) programs with AFRL.

The SBIRS Low operational system (EMD) is currently scheduled for deployment in 2006. The EMD program requirements are an extension of the FDS requirements, and more stringent. The major changes for EMD cryocooler requirements are increased duty cycle, higher cooling loads for the tracking sensors, increased cooling loads for the fore optics, complete mechanical and electronic redundancy, and higher tolerance to radiation environments.

As evidenced by specific cases discussed in this paper, cryocooler technology developers can underestimate the factors that contribute to cooler unreliability. Some of the potential contributors to cryocooler unreliability include wear, drift, fatigue, material creep, gaseous contamination, particulate/compound contamination and clogging, material and workmanship defects, inadequate machining process development, magnetic circuit degradation, assembly errors, material thermal expansion mismatches, and long-term alignment instability.

All potential failure modes and life limiting mechanisms have not been identified, and those that have are not completely understood or quantified. Also, various cryocooler concepts can have vastly different inherent failure modes and effects, as well as "graceful degradation" characteristics. Because of the importance of validating cryocoolers as long-life spacecraft components, a very high priority is placed on gathering cooler-specific life, reliability, and long-term performance data. However, for an endurance evaluation to have meaning and correlate to the long life and reliability characteristics of the cryocooler technology, care must be taken when examining the data from the cryocooler experiments. Experimental setups that include make-up gas (no hermeticity), gas cleaning, periodic rebuilding, operation at levels significantly below the capacity of the cooler, and inadequate or overly favorable environments will bias the endurance data gained from the experiment.

AFRL objectives for long term cryocooler endurance evaluation have evolved to meet the requirements for the demonstration of the lifetime and reliability of cryocooler technology for the Air Force (SBIRS Low), BMDO, and the DoD:

1. The focus of long life endurance evaluation of cryocooler technologies is on the characterization of long term performance degradation, system reliability, reliability contributors / detractors, the lifetime of the technology, and the development of proven methods for accelerated testing of long life space cryocoolers.

2. AFRL provides feedback in the form of technical reports and conference presentations of data and lessons learned to cryocooler and cryogenic technology developers, users, and spacecraft developers to aid in follow-on developments of emerging technology.

The AFRL Cryocooler Characterization Laboratory's (CCL) experiment facilities, procedures, equipment and instrumentation all serve to enable long-duration endurance evaluation data collection in environmental conditions closely simulating the space environment. Once underway, endurance evaluation is normally run until the cooler meets pre-defined failure criteria. If the test article continues to exhibit adequate performance past its design life, it will be allowed to run until it does meet the predetermined failure criteria. On the other hand, an endurance evaluation that requires 5 years of continuous data to support lifetime and reliability predictions as well as program requirements, will not meet the technical insertion freeze dates for critical Air Force and DoD programs. Although endurance data is valuable for understanding the life and reliability characteristics of a cryocooler, AFRL is working toward the development of proven accelerated testing methods to increase the understanding of the reliability of the design and reduce the technology insertion cycle time for emerging technologies. Information gathered during endurance evaluation is then made available to sponsors, technology users, cooler developers, and system integrators to help them refine system trades for both the coolers and their intended use on space platforms.

ENDURANCE EVALUATION OVERVIEW

Five cryocoolers are currently undergoing endurance evaluation or post-endurance disassembly and inspection at AFRL. Table 1 lists these coolers and their nominal operating conditions. Shaded areas are coolers in post endurance disassembly and inspection. These operating conditions are maintained at constant levels during the entire endurance trial phase except for periodic heat load/cold end temperature comparisons to previously established benchmark conditions. Cold end load / temperature checks against the baseline performance are usually conducted at 1 to 2 month intervals and are used to quantify time-dependent performance drift.

Table 1: Cryocooler Nominal Operating Conditions

Croycooler	T_C	Q_L	P_{in}	T_R	Endurance Phase
6020 PT	60 K	2.0 W	76 W	300+/-10 K	Endurance
3585 PT	35 K	0.85 W	200 W	300+/-10 K	Endurance
3503 PT	35 K	0.3 W	110 W	300 +/-10 K	Post-Endurance
SSRB	65 K	5 W	<240 W	300 K	Post-Endurance
CSSC	65 K	0.8 W	55 W	300+/-10 K	Post-Endurance

It should be noted that all of the coolers' heat rejection temperatures (T_R) are cycled above and below the nominal condition listed in Table 1, except for the SSRB. Cycling rejection temperatures during the experiment somewhat emulates the transient thermal effects experienced under normal space environmental usage and allows AFRL engineers to conduct baseline checks at different rejection temperatures. For comparison purposes, 300 K is defined as the nominal rejection temperature for all coolers. The rejection temperature cyclic range is varied depending on intended orbital transient profiles, cooler

design sensitivity to coefficient of thermal expansion effects, and thermodynamic performance limitations usually experienced at higher reject temperatures.

Endurance evaluation experiments can be run either in a thermal vacuum chamber or on a tabletop. The thermal vacuum chamber provides the most realistic vacuum and conductive thermal environment for the cryocooler. These chambers are reserved for cryocooler technology that is most representative of cryocooler family lines leading to flight technology. The tabletop configuration is used for cryocoolers that meet the criteria for long life endurance evaluation. These cryocoolers are reasonably hermetic and contribute to the heritage of emerging flight technology or technology alternatives. They contribute to the cryocooler lifetime and reliability database, but may not lead directly to flight technology.

During FY 99 three coolers entered the post-endurance evaluation disassembly and inspection phase. The Creare SSRB, the TRW 3503, and the Creare SSC completed their endurance evaluation at AFRL and are in the process of final inspection and analysis; by AFRL and by the cryocoolers' respective contractors. Further discussion on the initial observations from these experiments can be found in the following sections.

FY 98-99 ENDURANCE EVALUATION STATUS

Fiscal years 1998 and 1999 have been busy years for the AFRL CCL. In addition to normally busy characterization activities, three cryocoolers under endurance evaluation stopped operating for various reasons. As discussed in the introduction, there are a myriad of different mechanisms by which a cryocooler fails. Some of these mechanisms were plainly clear in the initial observations during post-endurance evaluation disassembly and inspection. Table 2 summarizes the current endurance evaluation activities at AFRL and the projected start dates of endurance evaluation of new coolers in the CCL. Subsequent discussion elaborates on the current status of each current experiment.

The TRW 6020 (2 W @ 60 K) Pulse Tube Cryocooler is currently under nominal conditions in endurance evaluation and has accumulated over 16,000 hours. The cold end temperature and input power history for the TRW 6020 can be seen in Figures 1 and 2. The 6020 was integrated and instrumented in a 24" thermal vacuum chamber. Its rejection temperature is set by a copper block interface to a computer controlled chilled fluid loop.

Apparent discrepancies in the characterization data have led AFRL to initiate a detailed review of all data on this cryocooler, the TRW 3503, and the TRW 3585. The first indication that there were data discrepancies was a distinct difference in thermodynamic performance compared to Jet Propulsion Laboratory data. Further data indicates that there was a possible shift in the parasitic load on the cold block of the cryocooler. Data reduction is continuing and should culminate in several technical reports that will be distributed to the appropriate users and developers. Additionally, the data will be summarized and reported in a conference forum for publication.

The TRW 3585 (0.85 W @ 35 K) Pulse Tube Cryocooler is still under endurance evaluation and has accumulated over 12,000 hours. This cryocooler is in a tabletop configuration. The tabletop setup does not provide the optimal endurance evaluation environmental conditions (the heat rejection now includes convective components as well as conductive), but it is being used since this particular cooler has limited follow-on applications. The TRW 3583 is being evaluated because it has significantly contributed to the family heritage of the TRW / Oxford Stirling compressor technology.

Table 2: AFRL Endurance Evaluation Status Summary

Cryocooler	Hours	Status
6020 PT	16872	This cooler is currently in Endurance Evaluation. Data to date shows the cooler operating within design margins and instrument error. Resolution of apparent discrepancies in the characterization data and the data correlation with JPL have not been completely quantified.
3585 PT	12386	This cooler is currently in Endurance Evaluation. Data to date shows the cooler operating within design margins and instrument error.
3503 PT	12093	The 3503 has completed endurance evaluation. After undergoing a significant overheat condition, the cooler continued to operate at degraded performance until April 99 when the cooler tripped and could not be restarted. The cooler internal gas was sampled and then taken to TRW for disassembly inspection. Discussion is underway with TRW to determine the future of the hardware.
SSRB	29,063	The SSRB shutdown in Dec 98 due to an alarm condition on the compressor. Subsequent attempts by AFRL and Creare personnel to restart the cooler were unsuccessful. They couldn't get the turboexpander to lift up and start spinning. Creare and AFRL personnel disassembled the turboexpander for inspection and analysis. Discussion is underway with Creare to determine the future of the hardware.
CSSC	13358	The CSSC shut down in December 98. Subsequent attempts by AFRL personnel to purge, re-fill, and re-start the cooler were not successful. At the present time, the CSSC endurance evaluation is complete and discussion is underway with Creare to determine the future of the hardware.
Projected Endurance Evaluation Experiments (hours are at current levels)		
Raytheon SSC II	500	Projected endurance evaluation start date of Oct 99.
Raytheon PSC	1000	Projected endurance evaluation start date of Nov 99.
MMS 10K	N/A	Projected endurance evaluation start date of May 00.
TRW mini PT	200	Projected endurance evaluation start date of Mar 00.
Ball Aerospace 35/60K	300	Projected endurance evaluation start date of Jun 00.

The TRW 3503 (0.3 W @ 35 K) Pulse Tube Cryocooler is currently in post-endurnace disassembly and inspection. This cooler suffered an environmental failure that exposed it to rejection temperatures up to 421 K for over 20 hours (Figure 1). After the overheat condition, the cryocooler showed typical performance degradation due to contamination, but it was allowed to continue its endurance evaluation. In April 1999, the 3503 tripped and was unable to restart. Subsequent investigation isolated the thermomechanical cooler as the culprit. AFRL and TRW performed a joint disassembly and inspection of the device. Prior to the disassembly inspection, AFRL and Pernicka Corp. conducted a sampling of the internal gas of the cryocooler. As expected, the analysis showed trace contamination gases. However, the source of the tripping was a loose locking nut on the capacitance sensor target that was not staked during the original build. At the time of the failure, the TRW 3503 had over 12,000 hours of operation. The cryocooler is currently at AFRL undergoing further stiction measurements on the compressor assembly. Plans are in the works to evaluate the need to rebuild, refill, and return the cooler to AFRL for characterization and endurance evaluation.

The Creare 5 W @ 65 K Single Stage Reverse Brayton (SSRB) cryocooler is also in post-endurance disassembly and inspection. The SSRB is a reverse Brayton device that employs fast spinning, micro-machined turbines to produce compression and expansion of

the working fluid (in this case, neon). This cryocooler engineering design model was delivered to AFRL (then Phillips Laboratory) with known gaseous contamination and atmosphere and water permeable o-ring seals. With these known flaws and characteristics, the decision was made to carry on with characterization and then long life endurance evaluation.

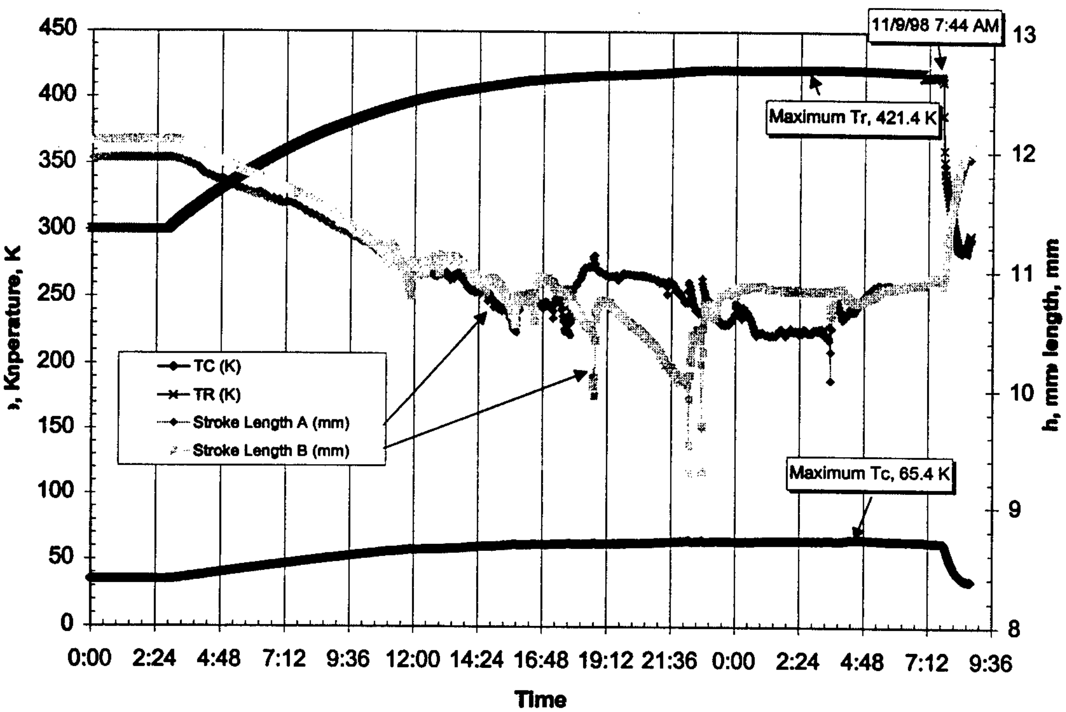

Figure 1. TRW 3503 Overheat Condition

This cryocooler tripped and shut down in December 1998 and was unable to spin up the turboexpander to re-start. All attempts by AFRL and Creare personnel on site did not achieve restart. During June 1999, Creare and AFRL personnel removed the turboexpander for disassembly and inspection. Preliminary results include the detection of foreign particulates in and near the moving components. At this time, the investigation is still underway. The final failure analysis will be completed jointly by Creare and AFRL, where Creare will outline the recommendations for the potential repair of the cryocooler. The total tally for operational hours on this unit was over 29,000 hours.

The Creare 65K SSC Diaphragm Stirling Cryocooler (CSSC) was configured in a tabletop format for portions of characterization and all of endurance evaluation. Due to a delivered flaw, the cryocooler was not hermetic and required a make-up helium gas bottle and periodic purge and fill gas cleaning cycles. Although the configuration of this endurance evaluation included a make-up gas system to compensate for the gas loss in the cooler, some useful data was gathered on the lifetime of the mechanical components of this diaphragm compressor design.

The CSSC tripped and shut down in December 1998. Subsequent attempts by AFRL personnel to purge, re-fill, and re-start the cooler were not successful. At the time of the shutdown, the CSSC had over 13,000 hours of operation. At the present time, the CSSC endurance evaluation is complete and discussion is underway with Creare to determine the future of the hardware.

TECHNOLOGY HERITAGE TO CANDIDATE SBIRS LOW CRYOCOOLERS

To support the SBIRS Low objectives for cryocooler reliability requirements, AFRL, under BMDO sponsorship, is continuing the endurance evaluation of past and current state-of-the-art cryocoolers. The endurance data is feed back to cryocooler developers and users to refine current and planned development programs. In addition to the examination of long term endurance, cryocooler developers and AFRL are pushing the elimination of "infant mortality" failures, which can be detected in appropriately designed "in-process" manufacturing tests, acceptance tests, and burn-in testing.

The SBIRS Low program office is particularly interested in the impact of cryocooler lifetime and reliability on the payload system. Table 3 has a summary of European and Domestic cryocooler life testing. However, this data must be taken with a grain of salt. There is significant variance in the experimental set-up of cryocooler endurance / life tests. These variances range from actual execution of the endurance / life environmental profile, the addition of make-up gas, to the vacuum environment. Even though a variance in testing may exist, the lessons learned on the mechanical units and their potential for life limiting mechanisms are extremely useful to follow on programs. To minimize the impact, SBIRS Low is planning for redundant cryocoolers and cryocooler electronics in their system design. The current development programs are utilizing lessons learned during previous developments and incorporating endurance data and lessons learned. Developers are emphasizing manufacturing processes to reduce the potential for failure over the long-term design life.

Table 3: Cryocooler Endurance Evaluation Summary (European and Domestic)*

Cryocooler	Heritage	Max Years Single Unit	Total Accumulated Years on all Units
	European Stirling Coolers		
23 Matra Marconi Space (MMS) 80K	These coolers have heritage to the TRW compressors and Ball Aerospace coolers.	6.4	21.8
14 MMS 50-80K		2.7	3.2
MMS, 1 20-50K unit		3.7	3.7
1 Oxford ESA 80K		8.1	8.1
2 Oxford/RAL ISAMS 80K flight		1.9	3.8
2 RAL ATSR1/ ATSR2 80K		4.8	8.3
	Domestic Coolers		
4 Raytheon ISSC 60K	These coolers have direct heritage to the Raytheon PSC	2.7	5.3
5 Raytheon FDS 35/60K		1.4	1.4
1 Creare 65K Single Stage Reverse Brayton	This cooler has direct heritage to the Creare NICMOS cooler	3.3	3.3
8 TRW mini-Stirling 60K	Some heritage to TRW compressor design in the larger units	1.7	3.3
15 TRW mini pulse tube 70/150K		3.6	9.0
4 TRW Pulse Tubes	Some heritage to TRW compressor design for the 95K High Efficiency Cryocooler	1.9	4.7
1 Ball Aerospace 30K	Direct heritage to the Ball Aerospace 35/60K three stage cryocooler	1.2	1.2
			Sum 79.2

** Source SBIRS Low Program Office and AFRL*

The impact to SBIRS Low from the 2 cryocooler "failures" at AFRL is minimal. The TRW 3503 pulse tube "failed" in two ways. First, the cooler was significantly overheated and had degraded performance. Second, the non-staked locking nut finally backed off and prevented any further operation. The overheat was not a failure of the cryocooler design, rather a testament to the robustness of the cryocooler itself and the non-staking issue was recognized by TRW long ago and all such parts are staked on all existing coolers. The Creare cooler presents a different side of the coin. This cooler operated for over 29,000 hours with excessive internal gaseous and particulate contamination. Again, this is a testament to the robustness of the technology and a lesson learned to improve the manufacturing process durning cryocooler builds.

SUMMARY AND CONCLUSIONS

Endurance evaluation at AFRL, other government laboratories, and industry facilities continues to add to the growing database of lifetime and reliability information on cryocooler technology. Cryocoolers in endurance evaluation at AFRL are producing volumes of long-term performance data. AFRL is actively engaged in improving the experimental test setup and remaining in close contact with government and industry partners to facilitate performance data feedback and share lessons learned.

Even cryocooler endurance "failures" are providing cryocooler developers and users with valuable lessons on manufacturing, hermeticity and working fluid cleanliness that will aid in the development of follow-on technology. It is certain that continuing endurance evaluation at AFRL will provide ever more meaningful lifetime and reliability data for mission enabling cryocooler applications in the future.

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